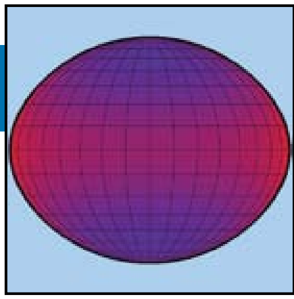

# Vega is a Rapidly Rotating Star

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A star's most important attributes are its mass, temperature, radius, composition, and rate of rotation. The Sun, for example, rotates once every 28 days, which implies a surface speed of about 2 kilometers per second at the equator. However, there are stars that rotate over 100 times faster. NRL scientists have recently shown that Vega, the brightest star in the constellation Lyra, is a member of this class of rapidly rotating stars. Due to its brightness, Vega has often been used as a standard for calibration purposes assuming it is a slowly rotating star, although there have been problems. The scientists have resolved these problems using the Navy Prototype Optical Interferometer to make observations showing that Vega is a rapid rotator with its axis of rotation pointing nearly directly at the earth. The techniques developed in the course of this work may someday be used to image objects in geosynchronous orbit.

## INTRODUCTION

Vega, the second brightest star in the northern sky, is located in Lyra, a prominent northern hemisphere constellation. Because of its brightness and easy accessibility to northern observers, Vega serves as standard calibrator for many branches of astrophysics. In the classification scheme that arranges stars according to their apparent temperature, Vega is the prototype main sequence *A* star with a temperature of about 10,000 K and a light blue sapphire color. Vega also serves as an absolute photometric standard from the ultraviolet through to the infrared region of the electromagnetic spectrum. Simple analysis of Vega's spectral lines suggests it is rotating slowly, so it has been used to test computer models of stellar atmospheres and stellar evolution.

However, over the years the feeling has developed that our understanding of Vega may not be complete. Models that predict the intrinsic luminosity of a star based on the strength of its hydrogen spectral lines find that Vega is twice as luminous as the models predict. This has led to the suggestion that Vega is rotating rapidly. Rapid rotation, however, causes the observed spectral lines from a star to be broadened due to the Doppler effect, but Vega shows narrow lines. To resolve this seeming contradiction, it was suggested more than ten years ago, based on analysis of subtle peculiarities in the shapes of its spectral lines, that Vega must be a rapid rotator seen nearly pole-on; i.e., its axis of rotation is pointing almost directly at the observer.

Rapid rotation changes the shape of a star: it becomes an oblate spheroid, flattened at the poles and extended at the equator. According to theory, the extended regions at the equator will have a lower temperature than at the poles, leading to an asymmetric brightness distribution, with the poles brighter than the equator. Thus, observations of Vega that show an asymmetric brightness distribution would confirm that it is a rapid rotator. Such observations require very high angular resolution to see details on the surface of the star. The Navy Prototype Optical Interferometer (NPOI), developed by NRL in partnership with the U.S. Naval Observatory and the Lowell Observatory, has recently made high-resolution observations confirming that Vega is a pole-on rapid rotator.

## RESOLVING THE SURFACE OF A SINGLE STAR

What angular resolution do we need to resolve structure on the surface of a star? We can get an approximate answer to this question by calculating the angular diameter of the Sun if it were placed at the distance of the nearest star. The Sun's physical diameter is about $14 \times 10^5$ km, and the distance to the nearest star, Alpha Centauri, is about $40 \times 10^{12}$ km. The ratio of these two numbers is about 35 nanoradians, or converting to angular measure, we find that the Sun would have an apparent angular diameter of 0.007 arc seconds, or 7 milliarcseconds (mas), at the distance of Alpha Centauri. Thus, in order to resolve surface structure on a star, we need a telescope that has a resolution of a few milliarcseconds.

The angular resolution of a telescope is inversely proportional to its diameter and directly proportional to the wavelength of light being observed. Thus, in order to increase the angular resolution of an observation we must either increase the diameter of the tele-

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scope or observe at shorter wavelengths. If we choose to observe at visible wavelengths, around 500 nm, then we find that the telescope must have a diameter of over 100 m in order to have a resolution of a few milliarcseconds. Clearly, we can't build a telescope of this size out of a single piece of glass; another approach is needed.

**SPARSE APERTURE IMAGING**

The technique developed by astronomers to get angular resolution beyond that possible with a single telescope is called *sparse aperture imaging*. Since constructing a single large telescope is not feasible, this technique uses several small telescopes separated by a few tens or hundreds of meters. The light from all the telescopes is combined at a central location. The resulting image has an angular resolution that is related to the largest separation between the individual small telescopes. The origins of this technique can be traced back to the work of the French physicist H. Fizeau more than 140 years ago; it was further developed toward the end of the 19th century by A. A. Michelson who taught at the U.S. Naval Academy and was the first American Nobel prize winner in physics.[1]

The underlying physical principle of sparse aperture imaging is the interference of light waves. If the light from two separate telescopes is combined, a pattern of light and dark bands appears. The spacing of the bands and the way they change as the separation of the telescopes is varied tells us something about the structure of the star being observed. This method of mapping the spatial structure of an object is called spatial interferometry, and the resulting instrument is called an *optical interferometer*.[2]

**THE NAVY PROTOTYPE OPTICAL INTERFEROMETER**

The Navy Prototype Optical Interferometer (NPOI), shown in Fig. 1, is located on Anderson Mesa near Flagstaff, Arizona, at an altitude of 2200 m.[3] The NPOI can combine the light from up to six small telescopes simultaneously, with the telescopes currently separated by up to 79 m. For visible light, the highest angular resolution is a bit more than 1 milliarcsecond, and routine observations can be made at a resolution of 1–2 milliarcseconds. This is just the resolution we need to start to resolve the surfaces of hot stars.

The individual telescopes of the NPOI are arranged in the shape of a Y, as seen in Fig. 1. The telescopes can be moved to different positions along the arms of the Y to change the angular resolution of the instrument. Each arm is 250 m long, so the largest spacing will eventually be 428 m between the tips of two of the arms. Figure 2 shows a ground level view of the center of the array with one of the individual telescope stations in the foreground. These stations use flat mirrors, called *siderostats*, which reflect the starlight into horizontal vacuum pipes (also visible in Fig. 2), from where the light continues on to the central optics laboratory to be combined with the light from other telescopes. The beam combination takes place on the large optical table shown in Fig. 3.

One of the most difficult challenges for ground-based optical astronomy is the distorting effect of turbulence in the earth's atmosphere, which blurs images made with single telescopes and degrades the resolution to about one arc second. Some of these effects can be mitigated by taking data rapidly; NPOI takes data at a rate of 500 samples per second. Additionally, it turns out that optical interferometers can eliminate the effects of atmospheric turbulence under certain conditions. If we combine the light from three telescopes that form a closed triangle, we can construct a quantity called the *closure phase*, which contains information about the symmetry or asymmetry of the surface of the star, while the atmospheric distortion is cancelled out. The closure phase plays a central role in our discovery of the rotation of Vega.

**RESOLVING A ROTATING VEGA**

Hugo von Zeipel at the Uppsala Observatory in Sweden developed the theory describing the shape of a rotating star more than 80 years ago. This theory shows that a rapidly rotating star takes on the shape of an oblate spheroid, flattened at the poles and bulging out at the equator. The rotational velocity at the equator can reach several hundred kilometers per second and the resulting centrifugal force (the force causing objects to fly off the surface) reduces the local force of gravity. If the equatorial velocity is high enough, the effective gravity will be very small and the star will break up. For the case of small effective gravity at the equator, von Zeipel's theory predicts a large drop in the local surface temperature that leads to a reduction in the surface brightness, an effect called "gravity darkening." Because of gravity darkening, the temperature, and therefore the brightness of the stellar surface, varies with latitude, being brightest (hottest) at the pole (where the tangential velocity is smallest) and lowest (coolest) at the equator (where the tangential velocity is a maximum). Figure 4 shows such a rapidly rotating star viewed in the equatorial plane. A rapidly rotating star with its rotation axis oriented at some arbitrary angle to the observer's line of sight will show an asymmetric intensity distribution with the bright polar cap appearing off center.

We have developed a computer model of a rotating star incorporating von Zeipel's theory.[4] The model generates parameters that describe the observations made with the NPOI on May 25, 2001 using three telescopes arranged in a triangle to give a single closure phase. We

**FIGURE 1**
Aerial view of the NPOI showing three arms arranged in a Y-shaped array; each arm is 250 meters long. There are two modes of operation. The astrometry mode is used to measure stellar positions and uses four fixed siderostats located in permanent huts near the center of the array. The imaging mode uses up to six movable siderostats that can be arranged along the arms of the array.

**FIGURE 2**
Ground-level view of the NPOI showing the center of the array. At left, one of the movable imaging siderostats is partially visible above its movable enclosure. Three of the permanent huts housing the astrometry siderostats are also visible, along with some of the horizontal vacuum pipes that carry the star light to the beam combination laboratory.

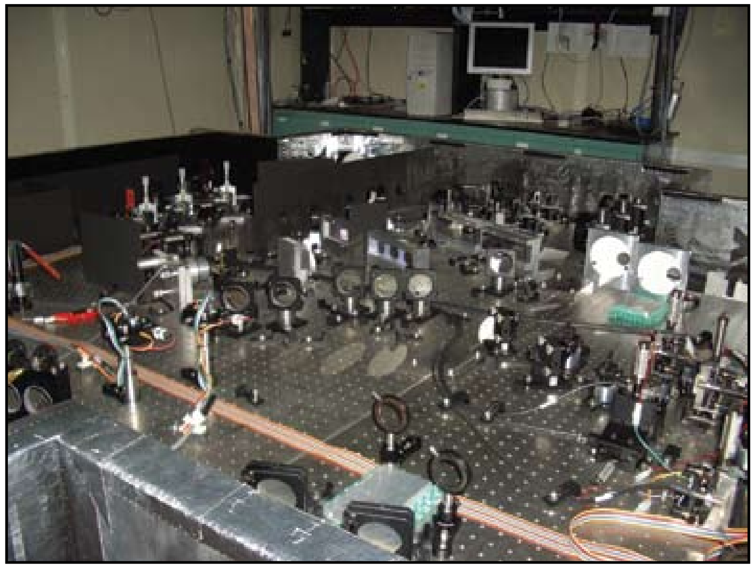

**FIGURE 3**
View of the optics laboratory showing the table where the light from up to six siderostats can be combined.

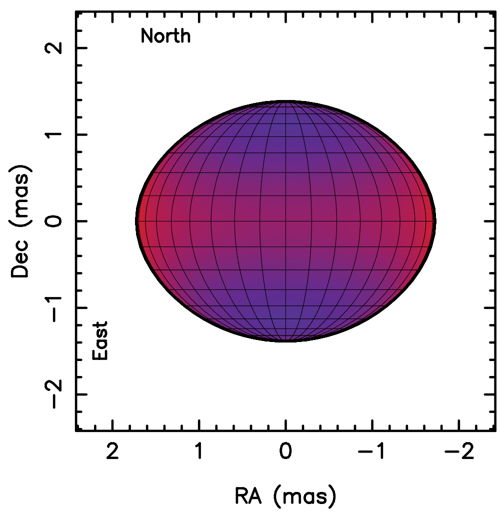


**FIGURE 4**
A model of a rapidly rotating star viewed in the equatorial plane, showing the extension at the equator and flattening at the poles. The surface temperature is shown in color, red representing cool regions and blue representing hot regions. Dec = declination; RA = right ascension.

then adjust the model parameters until we get the best fit to the data.

The result is shown in Fig. 5 where the open circles are data points from the NPOI and the solid line is the fit from the model. We find that Vega is rotating at nearly 93% of breakup velocity and its rotation axis is inclined 4.5° to the line of sight. In addition, the temperature at the equator is nearly 2,400 K lower than at the pole. A false-color image of the Vega model is shown in Fig. 6, where blue represents the bright parts and red the faint parts of the stellar surface.

As discussed in the introduction, Vega's rapid rotation will have an enormous impact on its use as a primary calibrator in astronomy. Since the emitted intensity varies over the surface, Vega cannot be used to infer intensities across the electromagnetic spectrum based on model atmospheres calculated assuming a single surface temperature. In addition, rapid rotation guarantees efficient mixing in the envelope, and the results of previous analyses of the composition of the surface could be substantially altered and will need to be revisited. The element composition directly affects the age of Vega derived from evolutionary models, and if the surface abundances previously derived (assuming slow rotation) apply throughout the star, then Vega may be nearly twice as old as previously thought.

## FUTURE APPLICATIONS

The Navy has a critical need to image objects in Earth's orbit. Standard ground-based imaging techniques often lack the resolution and sensitivity for this task. However, long baseline optical interferometry may be able to deliver the required detail. In fact, stars and satellites in geosynchronous orbit both present the same basic imaging challenges. Both are too distant to be resolved by existing single telescopes on the ground, and both classes of objects become resolved

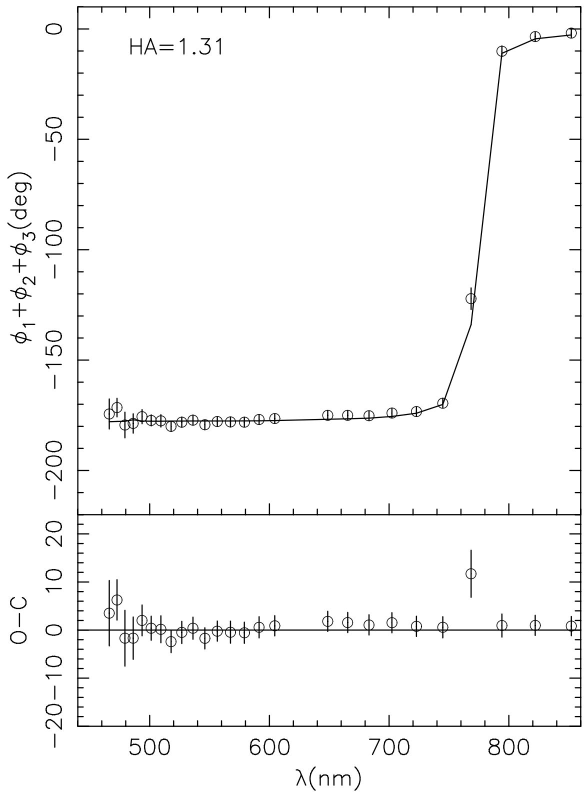


**FIGURE 5**
Fitting a model to the Vega data. In the upper panel, the open circles are the NPOI closure phase measurements and the solid line is the best-fit model. The lower panel shows the residuals, the difference between the measurements and the model.

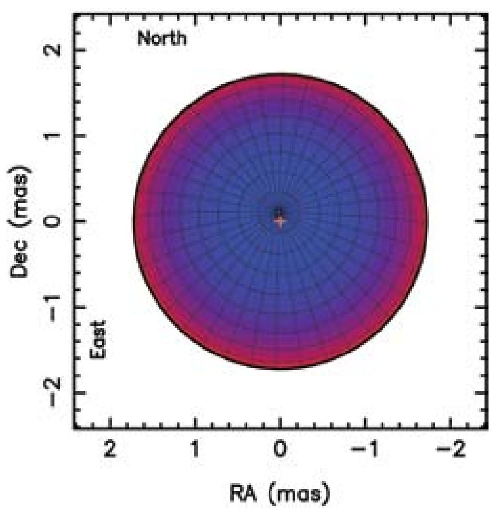


**FIGURE 6**
An image of Vega as seen from Earth based on the model of the NPOI data. The blue represents hot bright regions, while red represents cool faint regions. The orange cross is the subsolar point, the geometrical center of Vega as seen from Earth. Dec = declination; RA = right ascension.

with baselines (i.e., the distance between telescopes in an interferometric array) of several tens of meters. The main difference in this context is brightness. Stars are significantly brighter than spacecraft for a given angular size, and provide high signal-to-noise ratio objects for developing and testing analysis algorithms. Thus, the current work at the NPOI on imaging stellar surfaces will act as a pathfinder to imaging satellites in geosynchronous orbit.

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